

UNITED STATES PATENT APPLICATION

GRADED COMPOSITION METAL OXIDE TUNNEL BARRIER
INTERPOLY INSULATORS

INVENTORS

Dr. Jerome M. Eldridge
Dr. Kie Y. Ahn
Dr. Leonard Forbes

Schwegman, Lundberg, Woessner, & Kluth, P.A.
1600 TCF Tower
121 South Eighth Street
Minneapolis, Minnesota 55402
ATTORNEY DOCKET 1303.063US2
MICRON 02-0352.01

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Cross Reference To Related Applications

5 This application is a Continuation of U.S. patent application 10/177,096
filed on June 21, 2002 and a Continuation-in-Part of U.S. patent application
09/943,134 filed on August 30, 2001.

 This application is related to the following co-pending, commonly assigned
U.S. patent applications: "DRAM Cells with Repressed Memory Metal Oxide
10 Tunnel Insulators," serial number 09/945,395, "Flash Memory with Low Tunnel
Barrier Interpoly Insulators," serial number 09/945,507, "Dynamic Electrically
Alterable Programmable Memory with Insulating Metal Oxide Interpoly Insulators,"
serial number 09/945,498, "Field Programmable Logic Arrays with Metal Oxide
and/or Low Tunnel Barrier Interpoly Insulators," serial number 09/945,512, "SRAM
15 Cells with Repressed Floating Gate Memory, Metal Oxide Tunnel Interpoly
Insulators," serial number 09/945,554, "Programmable Memory Address and
Decode Devices with Low Tunnel Barrier Interpoly Insulators," serial number
09/945,500, "Programmable Array Logic or Memory with P-Channel Devices and
Asymmetrical Tunnel Barriers," serial number 10/028,001, and "Atomic Layer
20 Deposition of Metal Oxide and/or Low Tunnel Barrier Interpoly Insulators," serial
number 10/081818, each of which disclosure is herein incorporated by reference.

Field of the Invention

 The present invention relates generally to integrated circuits, and in
25 particular to programmable array type logic and/or memory devices with graded
composition metal oxide tunnel barrier interpoly insulators.

Background of the Invention

Flash memories have become widely accepted in a variety of applications ranging from personal computers, to digital cameras and wireless phones. Both INTEL and AMD have separately each produced about one billion integrated circuit chips in this technology.

The original EEPROM or EARPROM and flash memory devices described by Toshiba in 1984 used the interpoly dielectric insulator for erase. Various combinations of silicon oxide and silicon nitride were tried. However, the rough top surface of the polysilicon floating gate resulted in, poor quality interpoly oxides, sharp points, localized high electric fields, premature breakdown and reliability problems.

Widespread use of flash memories did not occur until the introduction of the ETOX cell by INTEL in 1988. This extremely simple cell and device structure resulted in high densities, high yield in production and low cost. This enabled the widespread use and application of flash memories anywhere a non-volatile memory function is required. However, in order to enable a reasonable write speed the ETOX cell uses channel hot electron injection, the erase operation which can be slower is achieved by Fowler-Nordhiem tunneling from the floating gate to the source. The large barriers to electron tunneling or hot electron injection presented by the silicon oxide-silicon interface, 3.2 eV, result in slow write and erase speeds even at very high electric fields. The combination of very high electric fields and damage by hot electron collisions in the oxide result in a number of operational problems like soft erase error, reliability problems of premature oxide breakdown and a limited number of cycles of write and erase.

Other approaches to resolve the above described problems include; the use of different floating gate materials, e.g. SiC, SiOC, GaN, and GaAlN, which exhibit a lower work function (see Figure 1A), the use of structured surfaces which increase the localized electric fields (see Figure 1B), and amorphous SiC gate insulators with

larger electron affinity, χ , to increase the tunneling probability and reduce erase time (see Figure 1C).

One example of the use of different floating gate (Figure 1A) materials is provided in US Patent no. 5,801,401 by L. Forbes, entitled "FLASH MEMORY
5 WITH MICROCRYSTALLINE SILICON CARBIDE AS THE FLOATING GATE
STRUCTURE." Another example is provided in US Patent no. 5,852,306 by L. Forbes, entitled "FLASH MEMORY WITH NANOCRYSTALLINE SILICON
FILM AS THE FLOATING GATE." Still further examples of this approach are provided in pending applications by L. Forbes and K. Ahn, entitled "DYNAMIC
10 RANDOM ACCESS MEMORY OPERATION OF A FLASH MEMORY DEVICE
WITH CHARGE STORAGE ON A LOW ELECTRON AFFINITY GaN OR
GaIN FLOATING GATE," serial no. 08/908098, and "VARIABLE ELECTRON
AFFINITY DIAMOND-LIKE COMPOUNDS FOR GATES IN SILICON CMOS
MEMORIES AND IMAGING DEVICES," serial no. 08/903452.

15 An example of the use of the structured surface approach (Figure 1B) is provided in US Patent no. 5,981,350 by J. Geusic, L. Forbes, and K.Y. Ahn, entitled
"DRAM CELLS WITH A STRUCTURE SURFACE USING A SELF
STRUCTURED MASK." Another example is provided in US Patent no. 6,025, 627
by L. Forbes and J. Geusic, entitled "ATOMIC LAYER EXPITAXY GATE
20 INSULATORS AND TEXTURED SURFACES FOR LOW VOLTAGE FLASH
MEMORIES."

Finally, an example of the use of amorphous SiC gate insulators (Figure 1C) is provided in US Patent Application serial no. 08/903453 by L. Forbes and K. Ahn, entitled "GATE INSULATOR FOR SILICON INTEGRATED CIRCUIT
25 TECHNOLOGY BY THE CARBURIZATION OF SILICON."

Additionally, graded composition insulators have been described by the same inventors, formed of silicon suboxide and silicon oxycarbide in combination with an SiO₂ layer, to increase the tunneling probability and reduce erase time. (See, L.

Forbes and J. M. Eldridge, "GRADED COMPOSITION GATE INSULATORS TO REDUCE TUNNELING BARRIERS IN FLASH MEMORY DEVICES," application serial no. 09/945,514.

5 However, all of these approaches relate to increasing tunneling between the floating gate and the substrate such as is employed in a conventional ETOX device and do not involve tunneling between the control gate and floating gate through an inter-poly dielectric.

Therefore, there is a need in the art to provide improved programmable array type logic and/or memory devices while avoiding the large barriers to electron
10 tunneling or hot electron injection presented by the silicon oxide-silicon interface, 3.2 eV, which result in slow write and erase speeds even at very high electric fields. There is also a need to avoid the combination of very high electric fields and damage by hot electron collisions in the which oxide result in a number of operational problems like soft erase error, reliability problems of premature oxide
15 breakdown and a limited number of cycles of write and erase. Further, when using an interpoly dielectric insulator erase approach, the above mentioned problems of having a rough top surface on the polysilicon floating gate which results in, poor quality interpoly oxides, sharp points, localized high electric fields, premature breakdown and reliability problems must be avoided.

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- US Patent 5,801,401, "Flash Memory With Microcrystalline Silicon Carbide As The Floating Gate Structure;";
- US Patent 5,852,306, "Flash Memory With Nanocrystalline Silicon Film As The
- 10 Floating Gate;";
- US Application Serial No. 08/908098, "Dynamic Random Access Memory Operation Of A Flash Memory Device With Charge Storage On A Low Electron Affinity GaN Or GaAlN Floating Gate;";
- US Application Serial No. 08/903452, "Variable Electron Affinity Diamond-Like
- 15 Compounds For Gates In Silicon CMOS Memories And Imaging Devices;";
- US Patent 5,981,350, "DRAM Cells With A Structure Surface Using A Self Structured Mask;";
- US Patent 6,025, 627 "Atomic Layer Epitaxy Gate Insulators and Textured Surfaces for Low Voltage Flash Memories;";
- 20 US Application Serial No. 08/903453, "Gate Insulator For Silicon Integrated Circuit Technology By The Carburization of Silicon;";
- US Application Serial No. 09/945514, "Graded Composition Gate Insulators to Reduce Tunneling Barriers In Flash Memory Devices;";
- US Patent 6,135,175, "Memory Address Decode Array With Vertical Transistors;"
- 25 U.S. Patent. 5,691,230, "Technique for Producing Small Islands of Silicon on Insulator;";
- US Application Serial No. 09/780169, "Flash Memory with Ultrathin Vertical Body Transistors;";

- US Application Serial No. 09/945507, "Flash Memory Devices With Metal Oxide and/or Low Tunnel Barrier Interpoly Insulators;"
- US Application Serial No. 09/945500, "Programmable Memory Address and Decode Devices With Metal Oxide and/or Low Tunnel Barrier Interpoly Insulators;"
- 5 US Application Serial No. 09/945512, "Field Programmable Logic Arrays With Metal Oxide and/or Low Tunnel Barrier Interpoly Insulators;"
- US Application Serial No. 09/945498, "DEAPROM With Insulating Metal Oxide Interpoly Insulators;"
- 10 US Application Serial No. 09/943134, "Programmable Array Type Logic and/or Memory Devices with Metal Oxide and/or Low Asymmetrical Tunnel Barrier Interpoly Insulators;"
- US Application Serial No. 10/028001, "Programmable Array Type Logic or Memory With P-Channel Devices and Asymmetrical Tunnel Barriers;"
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5 Nanolaminates," J. Electrochem. Soc. Vol. 148 (4), F63- F66 (2001).

Summary of the Invention

The above mentioned problems with programmable array type logic and/or
10 memory devices and other problems are addressed by the present invention and will be understood by reading and studying the following specification. Systems and methods are provided for programmable array type logic and/or memory devices with graded composition metal oxide tunnel barrier interpoly insulators.

In one embodiment of the present invention, a non-volatile memory cell, or
15 floating gate transistor, includes a first source/drain region and a second source/drain region separated by a channel region in a substrate. A floating gate opposes the channel region and is separated therefrom by a gate oxide. A control gate opposes the floating gate and is separated from the floating gate by a compositionally graded mixed metal oxide tunnel barrier intergate insulator. In one embodiment, the
20 intergate insulator is produced by low temperature chemical vapor deposition using a mixture of TiO_2 - ZrO_2 . In another embodiment, the intergate insulator is produced by low temperature chemical vapor deposition using a mixture of TiO_2 - HfO_2 . In another embodiment, the intergate insulator is produced by low temperature chemical vapor deposition using a mixture of ZrO_2 - HfO_2 . In another embodiment,
25 the intergate insulator is produced by low temperature chemical vapor deposition using a mixture of TiO_2 - ZrO_2 - HfO_2 . In another embodiment, intergate insulator is produced by a sequential atomic layer deposition process to make a graded Al_2O_3 - SiO_2 mixed oxide barrier oxide. Here, the sequential atomic layer deposition

produces a larger number of alumina mono-layers, interspersed with a lesser number of silica mono-layers, in the region nearest to the floating gate. In another embodiment, the intergate insulator is produced by oxidation of metal alloy films containing transition metals.

5 These and other embodiments, aspects, advantages, and features of the present invention will be set forth in part in the description which follows, and in part will become apparent to those skilled in the art by reference to the following description of the invention and referenced drawings or by practice of the invention. The aspects, advantages, and features of the invention are realized and attained by
10 means of the instrumentalities, procedures, and combinations particularly pointed out in the appended claims.

Brief Description of the Drawings

15 Figures 1A-1C illustrate a number of previous methods for reducing tunneling barriers in Flash memory.

Figure 2 illustrates one embodiment of a floating gate transistor, or non-volatile memory cell, according to the teachings of the present invention.

Figure 3 illustrates another embodiment of a floating gate transistor, or non-volatile memory cell, according to the teachings of the present invention.

20 Figure 4 is a perspective view illustrating an array of silicon pillars formed on a substrate as used in one embodiment according to the teachings of the present invention.

Figures 5A-5E are cross sectional views taken along cut line 5-5 from Figure 4 illustrating a number of floating gate and control gate configurations which are
25 included in the scope of the present invention.

Figures 6A-6D illustrate a number of address coincidence schemes can be used together with the present invention.

Figure 7A is an energy band diagram illustrating the band structure at vacuum level with the low tunnel barrier interpoly insulator according to the teachings of the present invention.

5 Figure 7B is an energy band diagram illustrating the band structure during an erase operation of electrons from the floating gate to the control gate across the low tunnel barrier interpoly insulator according to the teachings of the present invention.

Figure 7C is a graph plotting tunneling currents versus the applied electric fields (reciprocal applied electric field shown) for an number of barrier heights.

10 Figure 8 illustrates an energy band diagram useful in describing the properties of an embodiment of the present invention.

Figures 9A-9B illustrate different embodiments for the compositional profiles for the graded composition metal oxide tunnel barrier intergate insulators according to the teachings of the present invention.

15 Figure 10 illustrates a block diagram of an embodiment of an electronic system according to the teachings of the present invention.

Figure 11 is a schematic diagram illustrating a conventional NOR-NOR programmable logic array.

20 Figure 12 is a schematic diagram illustrating generally an architecture of one embodiment of a novel in-service programmable logic array (PLA) with floating gate transistors, or logic cells, having graded metal oxide tunnel barrier interpoly insulators according to the teachings of the present invention.

Figure 13 is a simplified block diagram of a high-level organization of an electronic system according to the teachings of the present invention.

25 Description of the Preferred Embodiments

In the following detailed description of the invention, reference is made to the accompanying drawings which form a part hereof, and in which is shown, by way of illustration, specific embodiments in which the invention may be practiced.

The embodiments are intended to describe aspects of the invention in sufficient detail to enable those skilled in the art to practice the invention. Other embodiments may be utilized and changes may be made without departing from the scope of the present invention. In the following description, the terms wafer and substrate are
5 interchangeably used to refer generally to any structure on which integrated circuits are formed, and also to such structures during various stages of integrated circuit fabrication. Both terms include doped and undoped semiconductors, epitaxial layers of a semiconductor on a supporting semiconductor or insulating material, combinations of such layers, as well as other such structures that are known in the
10 art.

The term "horizontal" as used in this application is defined as a plane parallel to the conventional plane or surface of a wafer or substrate, regardless of the orientation of the wafer or substrate. The term "vertical" refers to a direction perpendicular to the horizontal as defined above. Prepositions, such as "on", "side"
15 (as in "sidewall"), "higher", "lower", "over" and "under" are defined with respect to the conventional plane or surface being on the top surface of the wafer or substrate, regardless of the orientation of the wafer or substrate. The following detailed description is, therefore, not to be taken in a limiting sense, and the scope of the present invention is defined only by the appended claims, along with the full scope
20 of equivalents to which such claims are entitled.

The present invention, describes the use of graded composition metal oxide inter-poly dielectric insulators between the control gate and the floating gate of non-volatile memory cells. An example is shown in Figure 2 for a planar structure, or horizontal non-volatile memory cell. This non-volatile memory cell, as described
25 herein, can then be implemented in a number of programmable array type logic and/or memory devices according to the teachings of the present invention.

According to the teachings of the present invention. The use of a graded composition metal oxide films for this purpose offer a number of advantages including:

- 5 (i) Flexibility in selecting a range of smooth metal film surfaces and compositions that can be oxidized to form tunnel barrier insulators.
- (ii) Employing "low temperature oxidation" to oxidize metal alloy films to produce graded mixed oxide barriers of highly controlled thickness, composition, purity and uniformity, as well as employing low temperature CVD to produce the same.
- 10 (iii) Avoiding inadvertent inter-diffusion of the metal and silicon as well as silicide formation since the oxidation can be carried out at such low temperatures.
- (iv) Using metal oxides that provide desirably lower tunnel barriers, relative to barriers currently used such as SiO_2 .
- (v) Providing a wide range of higher dielectric constant oxide films with
15 improved capacitance characteristics.
- (vi) Providing a unique ability to precisely tailor tunnel oxide barrier properties for various device designs and applications.
- (vii) Permitting the use of thicker tunnel barriers, if needed, to enhance device performance and its control along with yield and reliability.
- 20 (viii) Developing layered oxide tunnel barriers by atomic layer deposition to produce a large number of mixed oxide tunnel barriers in order, for example, to enhance device yields and reliability more typical of single insulating layers.
- (ix) Eliminating soft erase errors caused by the current technique of tunnel erase from floating gate to the source.

25 Figure 2 illustrates one embodiment of a floating gate transistor, or non-volatile memory cell 200, according to the teachings of the present invention. As shown in Figure 2, the non-volatile memory cell 200 includes a first source/drain region 201 and a second source/drain region 203 separated by a channel region 205

in a substrate 206. A floating gate 209 opposes the channel region 205 and is separated therefrom by a gate oxide 211. A control gate 213 opposes the floating gate 209. According to the teachings of the present invention, the control gate 213 is separated from the floating gate 209 by a graded composition metal oxide tunnel barrier intergate insulator 215.

In one embodiment of the present invention, the graded composition metal oxide tunnel barrier intergate insulator 215 includes a graded composition metal oxide insulator which is produced by low temperature chemical vapor deposition using a mixture of TiO_2 - ZrO_2 . In another embodiment, the graded composition metal oxide tunnel barrier intergate insulator 215 includes a graded composition metal oxide insulator which is produced by low temperature chemical vapor deposition using a mixture of TiO_2 - HfO_2 . In another embodiment, the graded composition metal oxide tunnel barrier intergate insulator 215 includes a graded composition metal oxide insulator which is produced by low temperature chemical vapor deposition using a mixture of ZrO_2 - HfO_2 . In another embodiment, the graded composition metal oxide tunnel barrier intergate insulator 215 includes a graded composition metal oxide insulator which is produced by low temperature chemical vapor deposition using a mixture of TiO_2 - ZrO_2 - HfO_2 . In another embodiment, the graded composition metal oxide tunnel barrier intergate insulator 215 includes a graded composition metal oxide insulator which is produced by a sequential atomic layer deposition process to make a graded Al_2O_3 - SiO_2 mixed oxide barrier oxide. In this embodiment, the sequential atomic layer deposition produces a larger number of alumina mono-layers, interspersed with a lesser number of silica mono-layers, in the region nearest to the floating gate. In another embodiment, the graded composition metal oxide tunnel barrier intergate insulator 215 includes a graded composition metal oxide insulator which is produced by oxidation of metal alloy films containing transition metals.

In some embodiments according to the teachings of the present invention, as shown in Figure 2, the floating gate 209 includes a polysilicon floating gate 209 having a metal layer 216 formed thereon in contact with the graded composition metal oxide tunnel barrier intergate insulator 215. Likewise, the control gate 213 includes a polysilicon control gate 213 having a metal layer 217. In some embodiments, the metal layer 217 has a work function different from the metal layer 216 formed on the floating gate 209, formed thereon in contact with the graded composition metal oxide tunnel barrier intergate insulator 215. In one embodiment, metal layer 216 is formed of the same metal material used to form the graded composition metal oxide interpoly insulator 215. As stated above, the non-volatile memory cell, as described herein, can then be implemented in a number of programmable array type logic and/or memory devices according to the teachings of the present invention.

Figure 3 illustrates another embodiment of a floating gate transistor, or non-volatile memory cell 300, according to the teachings of the present invention. As shown in the embodiment of Figure 3, the non-volatile memory cell 300 includes a vertical non volatile memory cell 300. In this embodiment, the non-volatile memory cell 300 has a first source/drain region 301 formed on a substrate 306. A body region 307 including a channel region 305 is formed on the first source/drain region 301. A second source/drain region 303 is formed on the body region 307. Methods for forming such a vertical transistor structure are disclosed in US Patent no. 6,135,175, entitled "Memory Address Decode Array with vertical transistors, which is incorporated herein by reference. A floating gate 309 opposes the channel region 305 and is separated therefrom by a gate oxide 311. A control gate 313 opposes the floating gate 309. According to the teachings of the present invention, the control gate 313 is separated from the floating gate 309 by a graded composition metal oxide tunnel barrier intergate insulator 315.

In one embodiment of the present invention, the graded composition metal oxide tunnel barrier intergate insulator 315 includes a graded composition metal oxide insulator which is produced by low temperature chemical vapor deposition using a mixture of TiO_2 - ZrO_2 . In another embodiment, the graded composition metal oxide tunnel barrier intergate insulator 315 includes a graded composition metal oxide insulator which is produced by low temperature chemical vapor deposition using a mixture of TiO_2 - HfO_2 . In another embodiment, the graded composition metal oxide tunnel barrier intergate insulator 315 includes a graded composition metal oxide insulator which is produced by low temperature chemical vapor deposition using a mixture of ZrO_2 - HfO_2 . In another embodiment, the graded composition metal oxide tunnel barrier intergate insulator 315 includes a graded composition metal oxide insulator which is produced by low temperature chemical vapor deposition using a mixture of TiO_2 - ZrO_2 - HfO_2 . In another embodiment, the graded composition metal oxide tunnel barrier intergate insulator 315 includes a graded composition metal oxide insulator which is produced by a sequential atomic layer deposition process to make a graded Al_2O_3 - SiO_2 mixed oxide barrier oxide. In this embodiment, the sequential atomic layer deposition produces a larger number of alumina mono-layers, interspersed with a lesser number of silica mono-layers, in the region nearest to the floating gate. In another embodiment, the graded composition metal oxide tunnel barrier intergate insulator 315 includes a graded composition metal oxide insulator which is produced by oxidation of metal alloy films containing transition metals.

In some embodiments, as shown in Figure 3, the floating gate 309 includes a polysilicon floating gate 309 having a metal layer 316 formed thereon in contact with the graded composition metal oxide tunnel barrier intergate insulator 315. In some embodiments, the control gate 313 includes a polysilicon control gate 313 having a metal layer 317. In some embodiments, the metal layer 317 has a work function different from the metal layer 316 formed on the floating gate 309, formed

thereon in contact with the graded composition metal oxide tunnel barrier intergate insulator 315. As stated above, the non-volatile memory cell, as described herein, can then be implemented in a number of programmable array type logic and/or memory devices according to the teachings of the present invention.

5 As shown in Figure 3, the floating gate 309 includes a vertical floating gate 309 formed alongside of the body region 307. In the embodiment shown in Figure 3, the control gate 313 includes a vertical control gate 313 formed alongside of the vertical floating gate 309. According to the teachings of the present invention, the control gate 313 is separated from the floating gate 309 by a graded composition
10 metal oxide tunnel barrier intergate insulator 315.

 As will be explained in more detail below, the floating gate 309 and control gate 313 orientation shown in Figure 3 is just one embodiment for a vertical non volatile memory cell 300, according to the teachings of the present invention. In other embodiments, explained below, the floating gate includes a horizontally
15 oriented floating gate formed alongside of the body region. In this alternative embodiment, the control gate includes a horizontally oriented control gate formed above the horizontally oriented floating gate.

 Figure 4 is a perspective view illustrating an array of silicon pillars 400-1, 400-2, 400-3, . . . , 400-N, formed on a substrate 406 as used in one embodiment
20 according to the teachings of the present invention. As will be understood by one of ordinary skill in the art upon reading this disclosure, the substrates can be (i) conventional p-type bulk silicon or p-type epitaxial layers on p+ wafers, (ii) silicon on insulator formed by conventional SIMOX, wafer bonding and etch back or silicon on sapphire, or (iii) small islands of silicon on insulator utilizing techniques
25 such as described in more detail in U.S. patent no. 5,691,230, by Leonard Forbes, entitled "Technique for Producing Small Islands of Silicon on Insulator," issued 11/25/1997, which is incorporated herein by reference.

As shown in Figure 4, each pillar in the array of silicon pillars 400-1, 400-2, 400-3, . . . , 400-N, includes a first source/drain region 401 and a second source/drain region 403. The first and the second source/drain regions, 401 and 403, are separated by a body region 407 including channel regions 405. As shown in Figure 4, a number of trenches 430 separate adjacent pillars in the array of silicon pillars 400-1, 400-2, 400-3, . . . , 400-N. Trenches 430 are referenced in connection with the discussion which follows in connection with Figures 5A-5E.

Figures 5A-5E are cross sectional views taken along cut line 5-5 from Figure 4. As mentioned above in connection with Figure 3, a number of floating gate and control gate configurations are included in the present invention. Figure 5A illustrates one such embodiment of the present invention. Figure 5A illustrates a first source/drain region 501 and second source/drain region 503 for a non-volatile memory cell 500 formed according to the teachings of the present invention. As shown in Figure 5, the first and second source/drain regions, 501 and 503, are contained in a pillar of semiconductor material, and separated by a body region 507 including channel regions 505. As shown in the embodiments of Figures 5A-5E, the first source/drain region 501 is integrally connected to a buried sourceline 525. As one of ordinary skill in the art will understand upon reading this disclosure the buried sourceline 525 is be formed of semiconductor material which has the same doping type as the first source/drain region 501. In one embodiment, the sourceline 525 is formed of semiconductor material of the same doping as the first source/drain region 501, but is more heavily doped than the first source/drain region 501.

As shown in the embodiment of Figure 5A, a pair of floating gates 509-1 and 509-2 are formed in each trench 530 between adjacent pillars which form memory cells 500-1 and 500-2. Each one of the pair of floating gates, 509-1 and 509-2, respectively opposes the body regions 507-1 and 507-2 in adjacent pillars 500-1 and 500-2 on opposing sides of the trench 530.

In this embodiment, a single control gate 513 is shared by the pair of floating gates 509-1 and 509-2 on opposing sides of the trench 530. As one of ordinary skill in the art will understand upon reading this disclosure, the shared single control gate 513 can include an integrally formed control gate line. As shown in Figure 5A, such an integrally formed control gate line 513 can be one of a plurality of control gate lines which are each independently formed in the trench, such as trench 530, below the top surface of the pillars 500-1 and 500-2 and between the pair of floating gates 509-1 and 509-2. In one embodiment, according to the teachings of the present invention, each floating gate, e.g. 509-1 and 509-2, includes a vertically oriented floating gate having a vertical length of less than 100 nanometers.

As shown in the embodiment of Figure 5B, a pair of floating gates 509-1 and 509-2 are formed in each trench 530 between adjacent pillars which form memory cells 500-1 and 500-2. Each one of the pair of floating gates, 509-1 and 509-2, respectively opposes the body regions 507-1 and 507-2 in adjacent pillars 500-1 and 500-2 on opposing sides of the trench 530.

In the embodiment of Figure 5B, a plurality of control gate lines are again formed in trenches, e.g. trench 530, below the top surface of the pillars, 500-1 and 500-2, and between the pair of floating gates 509-1 and 509-2. However, in this embodiment, each trench, e.g. 530, houses a pair of control gate lines, shown as 513-1 and 513-2. Each one of the pair of control gate lines 513-1 and 513-2 addresses the floating gates, 509-1 and 509-2 respectively, on opposing sides of the trench 530. In this embodiment, the pair of control gate lines, or control gates 513-1 and 513-2 are separated by an insulator layer.

As shown in the embodiment of Figure 5C, a pair of floating gates 509-1 and 509-2 are again formed in each trench 530 between adjacent pillars which form memory cells 500-1 and 500-2. Each one of the pair of floating gates, 509-1 and 509-2, respectively opposes the body regions 507-1 and 507-2 in adjacent pillars 500-1 and 500-2 on opposing sides of the trench 530.

In the embodiment of Figure 5C, the plurality of control gate lines are disposed vertically above the floating gates. That is, in one embodiment, the control gate lines are located above the pair of floating gates 509-1 and 509-2 and not fully beneath the top surface of the pillars 500-1 and 500-2. In the embodiment of Figure 5C, each pair of floating gates, e.g. 509-1 and 509-2, in a given trench shares a single control gate line, or control gate 513.

As shown in the embodiment of Figure 5D, a pair of floating gates 509-1 and 509-2 are formed in each trench 530 between adjacent pillars which form memory cells 500-1 and 500-2. Each one of the pair of floating gates, 509-1 and 509-2, respectively opposes the body regions 507-1 and 507-2 in adjacent pillars 500-1 and 500-2 on opposing sides of the trench 530.

In the embodiment of Figure 5D, the plurality of control gate lines are disposed vertically above the floating gates. That is, in one embodiment, the control gate lines are located above the pair of floating gates 509-1 and 509-2 and not fully beneath the top surface of the pillars 500-1 and 500-2. However, in the embodiment of Figure 5D, each one of the pair of floating gates, e.g. 509-1 and 509-2, is addressed by an independent one of the plurality of control lines or control gates, shown in Figure 5D as 513-1 and 513-2.

As shown in the embodiment of Figure 5E, a single floating gate 509 is formed in each trench 530 between adjacent pillars which form memory cells 500-1 and 500-2. According to the teachings of the present invention, the single floating gate 509 can be either a vertically oriented floating gate 509 or a horizontally oriented floating gate 509 formed by conventional processing techniques, or can be a horizontally oriented floating gate 509 formed by a replacement gate technique such as described in a copending application, entitled "Flash Memory with Ultrathin Vertical Body Transistors," by Leonard Forbes and Kie Y. Ahn, application serial no. 09/780,169. In one embodiment of the present invention, the floating gate 509 has a vertical length facing the body region 505 of less than 100 nm. In another

embodiment, the floating gate 509 has a vertical length facing the body region 505 of less than 50 nm. In one embodiment, as shown in Figure 5E, the floating gate 509 is shared, respectively, with the body regions 507-1 and 507-2, including channel regions 505-1 and 505-2, in adjacent pillars 500-1 and 500-2 located on
5 opposing sides of the trench 530. In one embodiment, the control gate 513 includes a horizontally oriented control gate 513 formed above the horizontally oriented floating gate 509.

As one of ordinary skill in the art will understand upon reading this disclosure, in each of the embodiments described above in connection with Figures
10 5A-5E the floating gates 509 are separated from the control gate lines, or control gates 513 with a graded composition metal oxide tunnel barrier intergate insulator in accordance with the descriptions given above in connection with Figure 3. The modifications here are to use tunneling through the interpoly dielectric to realize flash memory devices. The vertical devices include an extra flexibility in that the
15 capacitors, e.g. gate oxide and intergate insulator, are easily fabricated with different areas. This readily allows the use of very high dielectric constant inter-poly dielectric insulators with lower tunneling barriers.

Figures 6A-6D illustrate that a number of address coincidence schemes can be used together with the present invention. Figure 6A illustrates a NOR flash
20 memory array 610 having a number of non-volatile memory cells 600-1, 600-2, 600-3, using a coincidence address array scheme. For purposes of illustration, Figure 6A shows a sourceline 625 coupled to a first source/drain region 601 in each of the number of non-volatile memory cells 600-1, 600-2, 600-3. The sourceline is shown oriented in a first selected direction in the flash memory array 610. In Figure 6A, a
25 number of control gate lines 630 are shown oriented in a second selected direction in the flash memory array 610. As shown in Figure 6A, the number of control gate lines 630 are coupled to, or integrally formed with the control gates 613 for the number of non-volatile memory cells 600-1, 600-2, 600-3. As shown in Figure 6A,

the second selected direction is orthogonal to the first selected direction. Finally, Figure 6A shows a number of bitlines 635 oriented in a third selected direction in the flash memory array 610. As shown in Figure 6A, the number of bitlines are coupled to the second source/drain regions in the number of non-volatile memory cells 600-1, 600-2, 600-3. In the embodiment shown in Figure 6A the third selected direction is parallel to the second selected direction and the number of control gate lines 630 serve as address lines. Also, as shown in Figure 6A, the flash memory array 610 includes a number of backgate or substrate/well bias address lines 640 coupled to the substrate.

Using Figure 6A as a reference point, Figures 6B-6D illustrate of top view for three different coincidence address scheme layouts suitable for use with the present invention. First, Figure 6B provides the top view layout of the coincidence address scheme described in connection with Figure 6A. That is, Figure 6B illustrates a number of sourcelines 625 oriented in a first selected direction, a number of control gate lines 630 oriented in a second selected direction, and a number of bitlines 635 oriented in a third selected direction for the flash memory array 600. As explained above in connection with Figure 6A, in this embodiment, the second and third selected direction are parallel to one another and orthogonal to the first selected direction such that the number of control gate lines 630 serve as address lines.

Figure 6C provides the top view layout of another coincidence address scheme according to the teachings of the present invention. This is, Figure 6C illustrates a number of sourcelines 625 oriented in a first selected direction, a number of control gate lines 630 oriented in a second selected direction, and a number of bitlines 635 oriented in a third selected direction for the flash memory array 600. In the embodiment of Figure 6C, the first selected direction and the third

selected direction are parallel to one another and orthogonal to the second selected direction. In this embodiment, the number of control gate lines 630 again serve as address lines.

5 Figure 6D provides the top view layout of yet another coincidence address scheme according to the teachings of the present invention. This is, Figure 6D illustrates a number of sourcelines 625 oriented in a first selected direction, a number of control gate lines 630 oriented in a second selected direction, and a number of bitlines 635 oriented in a third selected direction for the flash memory array 600. In the embodiment of Figure 6D, the first selected direction and the
10 second selected direction are parallel to one another and orthogonal to the third selected direction. In this embodiment, the number of bitlines 635 serve as address lines.

As will be apparent to one of ordinary skill in the art upon reading this disclosure, and as will be described in more detail below, write can still be achieved
15 by hot electron injection and/or, according to the teachings of the present invention, tunneling from the control gate to the floating gate. According to the teachings of the present invention, block erase is accomplished by driving the control gates with a relatively large positive voltage and tunneling from the metal on top of the floating gate to the metal on the bottom of the control gate.

20 Figure 7A is an energy band diagram illustrating the band structure at vacuum level with the graded composition metal oxide tunnel barrier interpoly insulator according to the teachings of the present invention. Figure 7A is useful in illustrating the reduced tunnel barrier off of the floating gate to the control gate and for illustrating the respective capacitances of the structure according to the teachings
25 of the present invention.

Figure 7A shows the graded composition metal oxide tunnel barriers, formed by low temperature CVD, by low temperature oxidation of metal alloy films, and by atomic layer deposition (ALD), as used in the present invention for easy erase.

Erase is achieved by the use of positive control gate voltages through the low tunnel barrier. In one embodiment, according to the teachings of the present invention, read utilizes positive control gate voltages with n-channel enhancement mode devices as described in the above referenced, copending applications, by the same
5 inventors, entitled "FLASH MEMORY DEVICES WITH METAL OXIDE AND/OR LOW TUNNEL BARRIER INTERPOLY INSULATORS," application serial no. 09/945,507, "PROGRAMMABLE MEMORY ADDRESS AND DECODE DEVICES WITH METAL OXIDE AND/OR LOW TUNNEL BARRIER INTERPOLY INSULATORS," application serial no. 09/945,500, "FIELD
10 PROGRAMMABLE LOGIC ARRAYS WITH METAL OXIDE AND/OR LOW TUNNEL BARRIER INTERPOLY INSULATORS, application serial no. 09/945,512, "DEAPROM WITH INSULATING METAL OXIDE INTERPOLY INSULATORS," application serial no. 09/945,498. In another embodiment, according to the teachings of the present invention, read utilizes negative control
15 gate voltages with n-channel depletion mode devices as described in the above referenced, copending application, by the same inventors, entitled "PROGRAMMABLE ARRAY TYPE LOGIC AND/OR MEMORY DEVICES WITH METAL OXIDE AND/OR LOW ASYMMETRICAL TUNNEL BARRIER INTERPOLY INSULATORS," application serial no. 09/943,134. In another
20 embodiment, according to the teachings of the present invention, read utilizes negative control gate voltages with p-channel enhancement mode devices as described in the above referenced, copending application, by the same inventors, entitled "PROGRAMMABLE ARRAY TYPE LOGIC OR MEMORY WITH P-CHANNEL DEVICES AND ASYMMETRICAL TUNNEL BARRIERS,"
25 application serial no. 10/028,001. Each of which above references is incorporated herein in full by reference for all purposes. Programming is accomplished by channel hot electron injection with n-channel devices and/or electron injection from

the control gate for both n-channel and p-channel devices and may or may not utilize positive substrate, well, or body bias.

Figure 7B is an energy band diagram illustrating the band structure during an erase operation of electrons from the floating gate 705 to the control gate 713 across the graded composition metal oxide tunnel barrier interpoly insulator 707 according to the teachings of the present invention. Figure 7B is similarly useful in illustrating the reduced tunnel barrier off of the floating gate 705 to the control gate 713 and for illustrating the respective capacitances of the structure according to the teachings of the present invention.

As shown in Figure 7B, the electric field is determined by the total voltage difference across the structure, the ratio of the capacitances (see Figure 7A), and the thickness of the graded composition interpoly dielectric 707.

$$t_{ig} = \frac{\epsilon_2 t_{ox}}{\epsilon_1}$$

The voltage across the graded composition interpoly dielectric 707 will be, $\Delta V_2 = V C_1 / (C_1 + C_2)$, where V is the total applied voltage. The capacitances, C, of the structures depends on the dielectric constant, ϵ_r , the permittivity of free space, ϵ_o , and the thickness of the insulating layers, t, and area, A, such that $C = \epsilon_r \epsilon_o A / t$, Farads/cm², where ϵ_r is the low frequency dielectric constant. The electric field across the graded composition interpoly dielectric insulator 707, having capacitance, C2, will then be $E_2 = \Delta V_2 / t_2$, where t2 is the thickness of this layer.

The tunneling current in erasing charge from the floating gate 705 by tunneling to the control gate 713 will then be as shown in Figure 7B given by an equation of the form:

$$J = B \exp(-E_o/E)$$

$$J = \frac{q^2 E^2}{4\pi\hbar\Phi} e^{-E_o/E} E_o = \frac{8\pi}{3} \frac{\sqrt{2mq\Phi}^{3/2}}{h}$$

where E is the electric field across the interpoly dielectric insulator 707 and E_0 depends on the barrier height. Practical values of current densities for aluminum oxide which has a current density of 1 A/cm^2 at a field of about $E = 1 \text{ V}/20 \text{ \AA} = 5 \times 10^{16} \text{ V/cm}$ are evidenced in a description by Pollack. Practical current densities
5 for silicon oxide transistor gate insulators which has a current density of 1 A/cm^2 at a field of about $E = 2.3 \text{ V}/23 \text{ \AA} = 1 \times 10^{17} \text{ V/cm}$ are evidenced in a description by T. P. Ma et al.

The lower electric field in the aluminum oxide interpoly insulator 707 for the same current density reflects the lower tunneling barrier (Φ_0) 721 of approximately 2
10 eV, shown in Figure 7B, as opposed to the 3.2 eV tunneling barrier (Φ_0) 723 of silicon oxide 703, also illustrated in Figure 7B.

Figure 7C is a graph plotting tunneling currents versus the applied electric fields (reciprocal applied electric field shown) for a number of barrier heights. Figure 7C illustrates the dependence of the tunneling currents on electric field
15 (reciprocal applied electric field) and barrier height. The fraction of voltage across the graded composition interpoly or graded composition intergate insulator, ΔV_2 , can be increased by making the area of the intergate capacitor, C_2 , (e.g. intergate insulator 707) smaller than the area of the transistor gate capacitor, C_1 (e.g. gate oxide 703). This would be required with high dielectric constant intergate dielectric
20 insulators 707 and is easily realized with the vertical floating gate structures described above in connection with Figures 3, and 5A-5E.

Methods of Formation

We disclose below several approaches for forming asymmetrical tunnel
25 barriers comprised of two or more metal oxides which have different tunnel barrier heights when contacted by the same electrode material. The barrier asymmetry is produced by combining the component metal oxides in such a way as to produce a gradient of their respective concentrations across the thickness of the resultant

mixed oxide tunnel barrier. Effects of these major compositional changes differ from those involving small departures from exact oxide stoichiometry that have been used in some of the previous disclosures referenced above. Such non-stoichiometric effects may also be present but will not be mentioned further in the following discussions which describe broad classes of approaches for forming a very broad range of asymmetrical barriers due to grading mixed oxide compositions.

As a starting point for forming a graded, mixed oxide barrier, we begin by noting that barriers for a range of metal oxides vary widely, from ~0.2 to 2.7 eV, depending on the contact metallurgy. (See Figure A).

TABLE A

	E_G	ϵ_r	ϵ_∞	χ	$\Phi_o(\text{Pt})$	$\Phi_o(\text{Al})$
Conventional Insulators						
SiO_2	~ 8eV	4	2.25	0.9 eV		3.2 eV
Si_3N_4	~ 5 eV	7.5	3.8			2.4 eV
Metal Oxides						
Al_2O_3	7.6 eV	9 - 11	3.4			~ 2 eV
NiO						
Transition Metal Oxides						
Ta_2O_5	4.65 – 4.85		4.8	3.3	2.0	0.8 eV
TiO_2	6.8	30-80	7.8	3.9	~ 1.2 eV	
ZrO_2	5 – 7.8	18.5-25	4.8	2.5		1.4
Nb_2O_5	3.1	35-50				
Y_2O_3	6		4.4			2.3
Gd_2O_3						
Perovskite Oxides						
$\text{SrBi}_2\text{Ta}_2\text{O}_3$	4.1		5.3	3.3	2.0	0.8 eV
SrTiO_3	3.3		6.1	3.9	1.4	0.2 eV
PbTiO_3	3.4		6.25	3.5	1.8	0.6 eV
PbZrO_3	3.7		4.8		~ 1.4	0.2 eV

Note, for example, that the barrier heights for Pt/TiO₂ and Pt/ Ta₂O₅ are ~ 1.2 and 2.0, respectively. Thus a barrier (comprised in part of TiO₂ and the remainder is Ta₂O₅) that is Ti-rich at the inner interface but less so at the outer will have an asymmetrical barrier that is lower at the inner and higher at the outer interface for the same (Pt) contact metal. Experimental barrier heights have not been determined for even homogeneous mixed oxide layers. However, one can estimate barrier heights by assuming that they will be intermediate between those of the component oxides. For example, a mixed oxide comprised of equal amounts of TiO₂ and Ta₂O₅ should have a barrier height near ~1.6 eV with a Pt contact. In the following sections, the present invention discloses how to form asymmetrical, mixed oxide tunnel barrier structures using a variety of oxides and practical processes. Although not discussed, it is quite clear that some of these processes can also be employed to produce graded tunnel barriers comprised of other insulating materials including oxy-nitrides, nitrides and possibly oxy-carbides and even carbides.

15

I. Graded Oxide Barriers by Low Temperature CVD. Binary transition metal oxide mixtures or solid solutions formed by CVD can be used to make several graded oxide systems. For example, in an article by Smith et al. the authors there determined that thin TiO₂, ZrO₂ and HfO₂ films can be formed on silicon substrates, using CVD and Group IV metal anhydrous nitrate precursors at temperatures of 250-300 degrees Celsius. While the nitrate compounds provide oxygen to produce the fully-oxidized metals, interfacial films of silicon oxide form as well as during the initial stage of metal dioxide deposition. The metal oxide films contain no carbon, hydrogen or halogen but have approximately 10-20% excess oxygen. There are several approaches for making graded oxide barriers using mixtures of: TiO₂- ZrO₂; TiO₂ -HfO₂; ZrO₂-HfO₂; and, TiO₂-ZrO₂-HfO₂. Within each group, one can tailor gradients to find those having the desired characteristics. The following examples outline how to fabricate these into structures. Processing details are omitted since

they will vary, depending on materials and devices, and are obvious to one skilled in the art. However it must be emphasized that the film depositions are to be carried out on surfaces free of native oxides and contaminants. This can be done in various ways including the use of low energy ion bombardment with inert gas ions and by
5 using systems that allow *in situ* cleaning, multiple depositions and other processes.

- Process A.**
1. Deposit a layer of Al on the floating gate to provide a planar, conducting surface.
 2. Deposit a layer of Ti-Zr alloy.
 - 10 3. Deposit a TiO_2 - ZrO_2 film using a modified process such as that described in the above article by Smith et al. Vary the ratio of $\text{Ti}(\text{NO}_3)_4/\text{Zr}(\text{NO}_3)_4$ reactants with time to produce: an initial oxide composition having a Ti/Zr concentration ratio close to that of the underlying alloy; and, a gradient that increases in Zr concentration
15 with thickness. A relative concentration- distance profile is shown schematically after oxide formation in Figure 9A. The outer barrier will be greater than the inner.
 4. Vacuum anneal under conditions needed to remove unstable, excess oxygen. Treatments must be found, not being known *a priori*.
 - 20 5. Complete the structure by adding the top electrode material such as: a Ti/Zr alloy, Al or a noble metal such as Pt or Pd, etc.

- Process B.**
1. Deposit a layer Al on the Si floating gate. This serves as an adhesion layer for the noble metal and prevents silicide formation.
 - 25 2. Deposit Pt or Pd, e.g., to act as an oxidation barrier.
 3. Deposit a graded oxide.
 4. Remove the excess oxygen.
 5. Add the top electrode layer. (See generally, Figure 9A).

Process C. 1. Modify the graded mixed oxides produced above in order to stabilize their as-deposited structure and prevent unwanted crystallization and grain growth. This can be done with small additions of glass-forming elements to the anhydrous metal nitrate reactants. For silicon, this might involve using a volatile halide compound since Si does not form nitrates or nitrides.

II. Graded Oxide Barriers by Oxidation of Metal Alloy Films can produce excellent tunnel barrier oxides. Manufacturing scale vacuum systems and thin film technologies have been used by IBM (beginning about 1970, a decade-long effort was carried out with IBM to develop a manufacturable technology for building super fast computers, using initially Josephson tunnel junctions formed by oxidation of Pb-In-Au films) and others to develop and qualify procedures for mass producing metal oxide tunnel devices for Josephson-based computer operations. Remarkably, 15 angstrom thick, oxide barriers can be built by oxidizing vacuum-deposited Pb-In-Au films. Such oxides are quite reproducible (to within approximately 0.2 angstroms in thickness) and have acceptably low levels of leakage. While such alloys would not be used here, the Josephson R and D activities and others as well provides an "existence theorem" demonstrating that viable manufacturing processes can be built around alloy film oxidation, even when the alloy films contain multiple phases and metals that differ greatly in their metallurgical properties, e.g., oxygen reactivities and mutual solubilities.

The present invention discloses the novel concept of forming and oxidizing graded-composition, metal alloy films for producing graded composition oxide tunnel barriers. The present invention uses for this purpose alloy films that typically contain Transition Metals (TM's) having important, common characteristics: 1) TM's mainly oxidize with a logarithmic-type time dependence, reaching self-limiting oxide thickness values (under 100 Å) in oxygen for temperatures < 400

degrees Celsius. 2) The TM's are refractory with very small diffusivities at low temperatures. Thus one can make TM alloy films having concentration gradients that are stable, provided the films are not heated excessively prior to oxidation. 3) Most TM's including lanthanides and alkaline earth metal possess very high and relatively similar affinities for oxygen. 4) Most very thin TM oxides formed by oxidation at low temperatures are amorphous or virtually so. 5) Although experimental data on low temperature oxidation of TM alloys is non-existent or nearly so. However, those skilled in the art can *a priori* choose particular TM alloy films that will obey logarithmic- time growth dependencies, thus allowing for the production of mixed oxide layers having highly-determinable thicknesses. 6) The relative concentrations of TM's in the growing oxide will correspond to those being converted to oxide in the underlying alloy. Thus graded composition oxides can be produced reproducibly. 7) The mixed TM oxides thus produced will be amorphous or nearly so. Based upon these considerations, one can sketch several approaches for producing TM graded Oxide tunnel junctions by low temperature oxidation of graded metal alloys. Processes D to F are given as examples.

Process D.

1. Deposit an Al layer on the Si floating gate.
2. Deposit a thin layer of Pt or Pd.
3. Deposit a Ti- Zr alloy film having a Zr/Ti concentration ratio which increases with thickness. Films can be made using: co-deposition with 2 Knudsen evaporation sources having fluxes programmed to vary with film thickness; co-deposition from 2 sputter guns; possibly by physical sputtering a single target, varying sputtering parameters with time.
4. Completely oxidize the alloy to form a mixed oxide wherein the zirconia concentration increases with oxide thickness while the titania concentration falls off correspondingly.

5. Complete the graded tunnel barrier by adding a top electrode material. The completed structure might look like that of Figure 9B.

Process E. 1. Deposit a graded layer of Ti- Zr alloy on the Si floating gate. The composition can be held constant until a given to be determined (TBD) thickness is reached before introducing a gradient in the alloy film. The constant-composition region is to be sufficient as to provide: a barrier to prevent Si oxidation; and, help fix the tunnel barrier height at its interface with oxide.

10 2. Oxidize the graded composition portion of the alloy. Some over-oxidation can be allowed since the intent is primarily to increase the zirconia/titania ratio on going towards the surface of the mixed oxide. Note that the thermal oxidation process will produce a mixture of oxides that require no subsequent oxygen out-gassing vacuum heat treatment.

15 3. Add the top electrode contact.

Process F This is similar to Processes D and E except that a small amount of silicon is added to the Ti- Zr alloy in order to promote retention of an amorphous oxide structure.

20 **III. Graded Oxide Barriers by ALD** can produce a large number of mixed oxide tunnel barriers. For example, Kukli et al have formed graded mixtures of Ta₂O₅, Nb₂O₅ and Al₂O₃ by ALD on soda lime substrates at 300 degrees Celsius, using precursors of Ta(OC₂H₅)₅, Nb(OC₂H₅)₅ and AlCl₃ and well established ALD recipes. They were able to, for example, vary the refractive index of Ta₂O₅ -Nb₂O₅ mixtures by making films progressively richer in Ta₂O₅. As another example, Ferguson et al used SiCl₄ and Al(CH₃)₃ precursors and ALD to sequentially coat BN particles at

roughly 300 degrees Celsius. Thus one might fabricate graded oxide films in various ways as evident from the examples G and H below:

- Process G.** Use the well-established chemistries in the references of Kukli et al to produce, for example, graded Al_2O_3 - Ta_2O_5 solid solution films whose alumina concentration increases with the mixed oxide thickness. The tunnel barrier of such a mixed oxide will be greater at the outer than the inner interface, for the same contact metallurgy.
- Process H.** Use nano-laminants comprised of different metal oxides. As one example, use sequential ALD processes to make a graded Al_2O_3 - SiO_2 mixed oxide barrier oxide. The sequencing will be such as to produce a larger number of alumina mono-layers, interspersed with a lesser number of silica mono-layers, in the region nearest to an inner interface with the floating gate. With increasing thickness of the nano-laminate, progressively increase the number of silica layers deposited, relative to the number of alumina layers. For example, one might have a sequence such as:
- F.G./ Al_2O_3 / Al_2O_3 / SiO_2 / Al_2O_3 / Al_2O_3 SiO_2 / SiO_2 / Al_2O_3 / SiO_2 / SiO_2 /C.G.

Where F.G. and C.G. represent the Floating Gate and Control Gate contacts, respectively. In such a layered dielectric, the barrier height of the alumina-rich region will be mitigated by the close proximity of silica while the silica-rich barrier will be lowered due to the presence of alumina 2 mono-layers distant from the C.G. This makes use of the principle that tunnel barriers are determined not only by the 1st contacting dielectric layer but also by the 2nd, 3rd, ...nth layers. Clearly the relative

influence on the effective tunnel barrier of a given “doping” layer will diminish rapidly with its distance from the electrode. Nevertheless one can certainly produce asymmetrical barriers in this fashion, with the ability to fine-tune the relative heights of each. It is also clear that other symmetrical tunnel barriers can be formed using
5 other ALD oxides.

One final comment. It appears that others have not graded nano-laminants for this purpose but have focused instead on their potential for gate dielectrics and optical applications.

10 Method of Operation

Write can be achieved by tunneling from the control gate to the floating gate by driving the control gate negative and/or channel hot electron injection as in conventional flash memory devices. Erase would be accomplished by driving the control gates with a relatively large positive voltage and tunneling from the metal on
15 top of the floating gate to the metal on the bottom of the control gate through the graded composition metal oxide tunnel barrier intergate insulators of the present invention. A graded composition metal oxide tunnel barrier between the floating gate and the control gate will make the erase operation easy.

In n-channel enhancement mode devices are used in the array, reading is
20 accomplished by driving the control gate with a smaller positive voltage. If no electrons are stored on the floating gate the transistor will turn on. If electrons are stored on the floating gate the transistor will not turn on or only turn on at a lower conductivity state. This constitutes the memory function. If n-channel depletion mode devices are used in the array then reading of the stored data is accomplished
25 with a zero or negative gate voltage, if the device conducts with zero or negative small gate voltage then there is no charge stored on the floating gate. If the floating gate is charged by stored electrons then the transistor will not conduct with zero or low negative gate voltages. The presence of stored charge on the floating gate

and/or applied negative gate voltages will result in electric fields in the
interpoly/intergate insulator. If the gate oxide is 2nm (20 Å) thick then the
capacitance is about 1.6×10^{-6} F/cm² and a 1 Volt difference will store a charge of
1.6x10⁻⁶ Coulombs/cm². A retention time of one second requires a leakage current
5 of less than about 10^{-6} Amps/cm², if as shown in Figure 7C the tunneling barrier is
2.0 eV and the electric field in the interpoly/intergate insulator is less than about
 2×10^6 V/cm then the current density will be 10^{-16} Amps/cm² and the retention time
 10^{+10} seconds. One year is about $3 \times 10^{+7}$ seconds, very long retention times can be
achieved by using low electric fields during read in conjunction with the larger
10 tunnel barrier during read.

During erase a positive voltage is applied to the control gate to tunnel
electrons off of the floating gate. If in this case during erase the electric field in the
interpoly/intergate insulator is about 2×10^6 V/cm and the erase barrier is as low as
1.25 eV then the erase current will be about 1 milliamp Amp/cm² and erase will be
15 about 1 millisecond. This simple illustration serves to show that a graded
composition tunneling barrier can make many orders of magnitude differences in the
time for the same charge to change by tunneling even at the same electric fields.
The electric field during erase can be increased if a faster erase time is required and
erase easily achieved in less than a microsecond. The lower tunneling barrier results
20 in a much faster erase at much lower electric fields and than in conventional flash
memory devices which require fields of 10^7 V/cm to achieve the erase currents of 1
Amp/cm² with a silicon oxide tunnel barrier of 3.2 eV. Thus, the graded
composition tunnel barriers of the present invention can serve to make erase of flash
memory type devices easy while insuring a long retention time during standby and
25 read operations.

System Level

Figure 10 illustrates a block diagram of an embodiment of an electronic system 1001 according to the teachings of the present invention. In the embodiment shown in Figure 10, the system 1001 includes a memory device 1000 which has an array of memory cells 1002, address decoder 1004, row access circuitry 1006,
5 column access circuitry 1008, control circuitry 1010, and input/output circuit 1012. Also, as shown in Figure 10, the circuit 1001 includes a processor 1014, or memory controller for memory accessing. The memory device 1000 receives control signals from the processor 1014, such as WE*, RAS* and CAS* signals over wiring or
10 metallization lines. The memory device 1000 is used to store data which is accessed via I/O lines. It will be appreciated by those skilled in the art that additional circuitry and control signals can be provided, and that the memory device 1000 has been simplified to help focus on the invention. At least one of the processor 1014 or memory device 1000 has a memory cell formed according to the embodiments of the
15 present invention. That is, at least one of the processor 1014 or memory device 1000 includes a graded composition metal oxide tunnel barrier interpoly insulator according to the teachings of the present invention.

It will be understood that the embodiment shown in Figure 10 illustrates an embodiment for electronic system circuitry in which the novel memory cells of the present invention are used. The illustration of system 1001, as shown in Figure 10,
20 is intended to provide a general understanding of one application for the structure and circuitry of the present invention, and is not intended to serve as a complete description of all the elements and features of an electronic system using the novel memory cell structures. Further, the invention is equally applicable to any size and
25 type of memory device 1000 using the novel memory cells of the present invention and is not intended to be limited to that described above. As one of ordinary skill in the art will understand, such an electronic system can be fabricated in single-

package processing units, or even on a single semiconductor chip, in order to reduce the communication time between the processor and the memory device.

Applications containing the novel memory cell of the present invention as described in this disclosure include electronic systems for use in memory modules,
5 device drivers, power modules, communication modems, processor modules, and application-specific modules, and may include multilayer, multichip modules. Such circuitry can further be a subcomponent of a variety of electronic systems, such as a clock, a television, a cell phone, a personal computer, an automobile, an industrial control system, an aircraft, and others.

10 Figure 11 shows a conventional NOR-NOR logic array 1100 which is programmable at the gate mask level by either fabricating a thin oxide gate transistor, e.g. logic cells 1101-1, 1101-2, . . . , 1101-N and 1103-1, 1103-2, . . . , 1103-N, at the intersection of lines in the array or not fabricating a thin oxide gate transistor, e.g. missing thin oxide transistors, 1102-1, 1102-2, . . . , 1102-N, at such
15 an intersection. As one of ordinary skill in the art will understand upon reading this disclosure, the same technique is conventionally used to form other types of logic arrays not shown. As shown in Figure 11, a number of depletion mode NMOS transistors, 1116 and 1118 respectively, are used as load devices.

The conventional logic array shown in Figure 11 includes a first logic plane
20 1110 which receives a number of input signals at input lines 1112. In this example, no inverters are provided for generating complements of the input signals. However, first logic plane 1110 can include inverters to produce the complementary signals when needed in a specific application.

First logic plane 1110 includes a number of thin oxide gate transistors, e.g.
25 transistors 1101-1, 1101-2, . . . , 1101-N. The thin oxide gate transistors, 1101-1, 1101-2, . . . , 1101-N, are located at the intersection of input lines 1112, and interconnect lines 1114. In the conventional PLA of Figure 11, this selective fabrication of thin oxide gate transistor, e.g. transistors 1101-1, 1101-2, . . . , 1101-N,

is referred to as programming since the logical function implemented by the programmable logic array is entered into the array by the selective arrangement of the thin oxide gate transistors, or logic cells, 1101-1, 1101-2, . . . , 1101-N, at the intersections of input lines 1112, and interconnect lines 1114 in the array.

5 In this embodiment, each of the interconnect lines 1114 acts as a NOR gate for the input lines 1112 that are connected to the interconnect lines 1114 through the thin oxide gate transistors, 1101-1, 1101-2, . . . , 1101-N, of the array. For example, interconnection line 1114A acts as a NOR gate for the signals on input lines 1112A and 1112B. That is, interconnect line 1114A is maintained at a high potential unless
10 one or more of the thin oxide gate transistors, 1101-1, 1101-2, . . . , 1101-N, that are coupled to interconnect line 1114A are turned on by a high logic level signal on one of the input lines 1112. When a control gate address is activated, through input lines 1112, each thin oxide gate transistor, e.g. transistors 1101-1, 1101-2, . . . , 1101-N, conducts which performs the NOR positive logic circuit function, an inversion of
15 the OR circuit function results from inversion of data onto the interconnect lines 1114 through the thin oxide gate transistors, 1101-1, 1101-2, . . . , 1101-N, of the array.

As shown in Figure 11, a second logic plane 1124 is provided which includes a number of thin oxide gate transistor, e.g. transistors 1103-1, 1103-2, . . . ,
20 1103-N. The thin oxide gate transistors, 1103-1, 1103-2, . . . , 1103-N, are located at the intersection of interconnect lines 1114, and output lines 1120. Here again, the logical function of the second logic plane 1124 is implemented by the selective arrangement of the thin oxide gate transistors, 1103-1, 1103-2, . . . , 1103-N, at the intersections of interconnect lines 1114, and output lines 1120 in the second logic
25 plane 1124. The second logic plane 1124 is also configured such that the output lines 1120 comprise a logical NOR function of the signals from the interconnection lines 1114 that are coupled to particular output lines 1120 through the thin oxide gate transistors, 1103-1, 1103-2, . . . , 1103-N, of the second logic plane 1124. Thus,

in Figure 11, the incoming signals on each line are used to drive the gates of transistors in the NOR logic array as the same is known by one of ordinary skill in the art and will be understood by reading this disclosure.

Figure 12 illustrates an embodiment of a novel in-service programmable logic array (PLA) formed according to the teachings of the present invention. In Figure 12, PLA 1200 implements an illustrative logical function using a two level logic approach. Specifically, PLA 1200 includes first and second logic planes 1210 and 1222. In this example, the logic function is implemented using NOR-NOR logic. As shown in Figure 12, first and second logic planes 1210 and 1222 each include an array of, logic cells, non-volatile memory cells, or floating gate driver transistors, 1201-1, 1201-2, . . . , 1201-N, and 1202-1, 1202-2, . . . , 1202-N respectively, formed according to the teachings of the present invention, e.g. including a graded composition metal oxide tunnel barrier interpolary insulator. The floating gate driver transistors, 1201-1, 1201-2, . . . , 1201-N, and 1202-1, 1202-2, . . . , 1202-N, have their first source/drain regions coupled to source lines or a conductive source plane, as shown and described in more detail in connection with Figures 3 and 5E. These floating gate driver transistors, 1201-1, 1201-2, . . . , 1201-N, and 1202-1, 1202-2, . . . , 1202-N are configured to implement the logical function of FPLA 1200. The floating gate driver transistors, 1201-1, 1201-2, . . . , 1201-N, and 1202-1, 1202-2, . . . , 1202-N are shown as n-channel floating gate transistors. However, the invention is not so limited. Also, as shown in Figure 12, a number of p-channel metal oxide semiconductor (PMOS) transistors are provided as load device transistors, 1216 and 1224 respectively, having their source regions coupled to a voltage potential (VDD). These load device transistors, 1216 and 1224 respectively, operate in complement to the floating gate driver transistors, 1201-1, 1201-2, . . . , 1201-N, and 1202-1, 1202-2, . . . , 1202-N to form load inverters.

It is noted that the configuration of Figure 12 is provided by way of example and not by way of limitation. Specifically, the teachings of the present application

are not limited to programmable logic arrays in the NOR-NOR approach. Further, the teachings of the present application are not limited to the specific logical function shown in Figure 12. Other logical functions can be implemented in a programmable logic array, with the floating gate driver transistors, 1201-1, 1201-2, . . ., 1201-N, and 1202-1, 1202-2, . . ., 1202-N and load device transistors, 1216 and 1224 respectively, of the present invention, using any one of the various two level logic approaches.

First logic plane 1210 receives a number of input signals at input lines 1212. In this example, no inverters are provided for generating complements of the input signals. However, first logic plane 1210 can include inverters to produce the complementary signals when needed in a specific application.

First logic plane 1210 includes a number of floating gate driver transistors, 1201-1, 1201-2, . . ., 1201-N, that form an array such as an array of non-volatile memory cells, or flash memory cells. The floating gate driver transistors, 1201-1, 1201-2, . . ., 1201-N, are located at the intersection of input lines 1212, and interconnect lines 1214. Not all of the floating gate driver transistors, 1201-1, 1201-2, . . ., 1201-N, are operatively conductive in the first logic plane. Rather, the floating gate driver transistors, 1201-1, 1201-2, . . ., 1201-N, are selectively programmed, as described in detail below, to respond to the input lines 1212 and change the potential of the interconnect lines 1214 so as to implement a desired logic function. This selective interconnection is referred to as programming since the logical function implemented by the programmable logic array is entered into the array by the floating gate driver transistors, 1201-1, 1201-2, . . ., 1201-N, that are used at the intersections of input lines 1212, and interconnect lines 1214 in the array.

In this embodiment, each of the interconnect lines 1214 acts as a NOR gate for the input lines 1212 that are connected to the interconnect lines 1214 through the floating gate driver transistors, 1201-1, 1201-2, . . ., 1201-N, of the array 1200. For example, interconnection line 1214A acts as a NOR gate for the signals on input

lines 1212A, 1212B and 1212C. Programmability of the vertical floating gate driver transistors, 1201-1, 1201-2, . . . , 1201-N is achieved by charging the vertical floating gates. When the vertical floating gate is charged, that floating gate driver transistor, 1201-1, 1201-2, . . . , 1201-N will remain in an off state until it is reprogrammed.

- 5 Applying and removing a charge to the vertical floating gates is performed by tunneling charge between the floating gate and control gates of the floating gate driver transistors, 1201-1, 1201-2, . . . , 1201-N through a low tunnel barrier interpoly, or intergate insulator as described in detail above and in connection with Figures 2-7C. A floating gate driver transistors, 1201-1, 1201-2, . . . , 1201-N
10 programmed in an off state remains in that state until the charge is removed from its vertical floating gate.

- Floating gate driver transistors, 1201-1, 1201-2, . . . , 1201-N not having a corresponding vertical floating gate charged operate in either an on state or an off state, wherein input signals received by the input lines 1212A, 1212B and 1212C
15 determine the applicable state. If any of the input lines 1212A, 1212B and 1212C are turned on by input signals received by the input lines 1212A, 1212B and 1212C, then a ground is provided to load device transistors 1216. The load device transistors 1216 are attached to the interconnect lines 1214. The load device transistors 1216 provide a low voltage level when any one of the floating gate driver
20 transistors, 1201-1, 1201-2, . . . , 1201-N connected to the corresponding interconnect line 1214 is activated. This performs the NOR logic circuit function, an inversion of the OR circuit function results from inversion of data onto the interconnect lines 1214 through the floating gate driver transistors, 1201-1, 1201-2, . . . , 1201-N of the array 1200. When the floating gate driver transistors, 1201-1,
25 1201-2, . . . , 1201-N are in an off state, an open is provided to the drain of the load device transistors 1216. The VDD voltage level is applied to corresponding input lines, e.g. the interconnect lines 1214 for second logic plane 1222 when a load device transistors 1216 is turned on by a clock signal received at the gate of the load

device transistors 1216 (Φ). Each of the floating gate driver transistors, 1201-1, 1201-2, . . . , 1201-N described herein are formed according to the teachings of the present invention as described in detail in connection with Figures 2-7C.

In a similar manner, second logic plane 1222 comprises a second array of floating gate driver transistors, 1202-1, 1202-2, . . . , 1202-N that are selectively programmed to provide the second level of the two level logic needed to implement a specific logical function. In this embodiment, the array of floating gate driver transistors, 1202-1, 1202-2, . . . , 1202-N is also configured such that the output lines 1220 comprise a logical NOR function of the signals from the interconnection lines 1214 that are coupled to particular output lines 1220 through the floating gate driver transistors, 1202-1, 1202-2, . . . , 1202-N of the second logic plane 1222.

Programmability of the vertical floating gate driver transistors, 1202-1, 1202-2, . . . , 1202-N is achieved by charging the vertical floating gate. When the vertical floating gate is charged, that floating gate driver transistor, 1202-1, 1202-2, . . . , 1202-N will remain in an off state until it is reprogrammed. Applying and removing a charge to the vertical floating gates is performed by tunneling charge between the floating gate and control gates of the floating gate driver transistors, 1201-1, 1201-2, . . . , 1201-N through a low tunnel barrier interpoly, or intergate insulator as described in detail above and in connection with Figures 2-7C. A floating gate driver transistor, 1202-1, 1202-2, . . . , 1202-N programmed in an off state remains in that state until the charge is removed from the vertical floating gate.

Floating gate driver transistors, 1202-1, 1202-2, . . . , 1202-N not having a corresponding vertical floating gate charged operate in either an on state or an off state, wherein signals received by the interconnect lines 1214 determine the applicable state. If any of the interconnect lines 1214 are turned on, then a ground is provided to load device transistors 1224 by applying a ground potential to the source line or conductive source plane coupled to the transistors first source/drain region as described herein. The load device transistors 1224 are attached to the output lines

1220. The load device transistors 1224 provide a low voltage level when any one of the floating gate driver transistors, 1202-1, 1202-2, . . . , 1202-N connected to the corresponding output line is activated. This performs the NOR logic circuit function, an inversion of the OR circuit function results from inversion of data onto
5 the output lines 1220 through the floating gate driver transistors, 1202-1, 1202-2, . . . , 1202-N of the array 1200. When the floating gate driver transistors, 1202-1, 1202-2, . . . , 1202-N are in an off state, an open is provided to the drain of the load device transistors 1224. The VDD voltage level is applied to corresponding output lines 1220 for second logic plane 1222 when a load device transistor 1224 is turned on by
10 a clock signal received at the gate of the load device transistors 1224 (Φ). In this manner a NOR-NOR electrically programmable logic array is most easily implemented utilizing the normal PLA array structure. Each of the floating gate driver transistors, 1202-1, 1202-2, . . . , 1202-N described herein are formed according to the teachings of the present invention as described in detail in
15 connection with Figures 2-7C.

Thus Figure 12 shows the application of the novel, non-volatile floating gate transistors with low tunnel barrier intergate insulators in a logic array. If a floating gate driver transistors, 1201-1, 1201-2, . . . , 1201-N, and 1202-1, 1202-2, . . . , 1202-N, is programmed with a negative charge on the vertical floating gate it is effectively
20 removed from the array. In this manner the array logic functions can be programmed even when the circuit is in the final circuit or in the field and being used in a system.

The absence or presence of stored charge on the floating gates is read by addressing the input lines 1212 or control gate lines and y-column/sourcelines to
25 form a coincidence in address at a particular floating gate. The control gate line would for instance be driven positive at some voltage of 1.0 Volt and the y-column/sourceline grounded, if the floating gate is not charged with electrons then the transistor would turn on tending to hold the interconnect line on that particular

row down indicating the presence of a stored "one" in the cell. If this particular floating gate is charged with stored electrons, the transistor will not turn on and the presence of a stored "zero" indicated in the cell. In this manner, data stored on a particular floating gate can be read.

5 Programming can be achieved by hot electron injection. In this case, the interconnect lines, coupled to the second source/drain region for the non-volatile memory cells in the first logic plane, are driven with a higher drain voltage like 2 Volts for 0.1 micron technology and the control gate line is addressed by some nominal voltage in the range of twice this value. Electrons can also be transferred
10 between the floating gate and the control gate through the low tunnel barrier intergate insulator to selectively program the non-volatile memory cells, according to the teachings of the present invention, by the address scheme as described above in connection with Figures 6A-6C. Erasure is accomplished by driving the control gate line with a large positive voltage and the sourceline and/or backgate or
15 substrate/well address line of the transistor with a negative bias so the total voltage difference is in the order of 3 Volts causing electrons to tunnel off of the floating gates to the control gates. Writing can be performed, as also described above, by either normal channel hot electron injection, or according to the teachings of the present invention, by driving the control gate line with a large negative voltage and
20 the sourceline and/or backgate or substrate/well address line of the transistor with a positive bias so the total voltage difference is in the order of 3 Volts causing electrons to tunnel off of the control gates to the floating gates. According one embodiment of the present invention, data can be erased in "bit pairs" since both floating gates on each side of a control gate can be erased at the same time. This
25 architecture is amenable to block address schemes where sections of the array are erased and reset at the same time.

One of ordinary skill in the art will appreciate upon reading this disclosure that a number of different configurations for the spatial relationship, or orientation

of the input lines 1212, interconnect lines 1214, and output lines 1220 are possible. That is, the spatial relationship, or orientation of the input lines 1212, interconnect lines 1214, and output lines 1220 can parallel the spatial relationship, or orientation configurations detailed above for the floating gates and control gates as described in connection with Figures 5A-5E.

Figure 13 is a simplified block diagram of a high-level organization of an electronic system 1300 according to the teachings of the present invention. As shown in Figure 13, the electronic system 1300 is a system whose functional elements consist of an arithmetic/logic unit (ALU), e.g. processor 1320, a control unit 1330, a memory unit 1340, or memory device 1340, and an input/output (I/O) device 1350. Generally such an electronic system 1300 will have a native set of instructions that specify operations to be performed on data by the ALU 1320 and other interactions between the ALU 1320, the memory device 1340 and the I/O devices 1350. The memory devices 1340 contain the data plus a stored list of instructions.

The control unit 1330 coordinates all operations of the ALU 1320, the memory device 1340 and the I/O devices 1350 by continuously cycling through a set of operations that cause instructions to be fetched from the memory device 1340 and executed. In service programmable logic arrays, according to the teachings of the present invention, can be implemented to perform many of the logic functions performed by these components. With respect to the ALU 1320, the control unit 1330 and the I/O devices 1350, arbitrary logic functions may be realized in the "sum-of-products" form that is well known to one skilled in the art. A logic function sum-of-products may be implemented using any of the equivalent two-level logic configurations: AND-OR, NAND-NAND, NOR-OR, OR-NOR, AND-NOR, NAND-AND or OR-AND, and using the novel non-volatile memory cells of the present invention.

CONCLUSION

Graded composition metal oxide barrier tunnel interpoly insulators are
5 described between the floating gate and control gate in a flash memory type devices
to form programmable array logic and memory devices. The graded composition
metal oxide barrier insulators, ~ 2.0 eV, are easily fabricated by the oxidation of a
transition metal or a composite metal layer. While the amount of charge stored on
the floating gate is small the transistor provides gain and charge multiplication
10 resulting in a large output signal and ease of reading the stored data. If there is an
adverse capacitance ratio due to a large difference of dielectric constants then the
vertical gate structures described previously can be employed.

Write can be achieved by the normal channel hot electron injection and gate
current through the silicon oxide to the floating gate. This is done by selecting a
15 particular column by applying a high control gate voltage and applying relatively
large drain voltage as is done with conventional ETOX memory devices. However,
according to the teachings of the present invention, write can also be accomplished
by applying a positive voltage to the substrate or well select line and a large negative
voltage to the control gates, electrons will tunnel from the control gate to the
20 floating gate. The graded composition metal oxide tunnel barrier will provide an
easy write operation and the selection of the substrate or well bias will provide
selectivity and address only one device.

According to the teachings of the present invention, erase is achieved by
providing a negative voltage to the substrate or well address line and a large positive
25 voltage to the control gate. This causes electrons to tunnel off of the floating gate on
to the control gate. A whole row can be erased by addressing all the column lines
along that row and a block can be erased by addressing multiple row back gate or
substrate/well address lines.

It has been shown that the graded composition metal oxide tunnel barrier interpoly insulators of the present invention avoid the large barriers to electron tunneling or hot electron injection presented by the silicon oxide-silicon interface, 3.2 eV, which result in slow write and erase speeds even at very high electric fields.

- 5 The present invention also avoids the combination of very high electric fields and damage by hot electron collisions in the which oxide result in a number of operational problems like soft erase error, reliability problems of premature oxide breakdown and a limited number of cycles of write and erase. Further, the graded composition metal oxide tunnel barrier interpoly dielectric insulator erase approach,
- 10 of the present invention remedies the above mentioned problems of having a rough top surface on the polysilicon floating gate which results in, poor quality interpoly oxides, sharp points, localized high electric fields, premature breakdown and reliability problems.